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A FRACTURE AND BALLISTIC PENETRATION RESISTANT LAMINATE

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A new metal/metal laminate has been conceived and developed in ARRADCOM, consisting of explosively bonded alternate layers of titanium and aluminum alloy sheets. Intended at first to give improved fatigue resistance in helicopter components, the laminate is found to provide improved impact and ballistic penetration resistance as well. In comparison to monolithic metal components or adhesively bonded laminates it can provide decreased weight and

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20. ABSTRACT (CONT'D)

increased durability and survivability for vehicles and craft subject to ballistic impact damage.

Three-layer and five-layer specimens of Ti-6AL-4V/2024-T3 laminate have been tested for resistance to through-the-thickness impact and ballistic penetration and for after-damage fatigue crack propagation. They were compared with rolled plate specimens of 6061-T6 aluminum alloy and rolled homogeneous steel armor (RHS) using 0.30 caliber fragment simulator projectiles (FSP). The Protection (V_{50}) Ballistic Limit Velocity and the fatigue life (N_f) remaining after ballistic penetration damage were measured on the same specimens. The fatigue crack propagation life was measured in compact specimens made from the ballistically damaged panels, with the crack initiated in the penetration damage site and grown to failure of the specimen.

The five-layer laminate having volume proportions of 60 percent aluminum and 40 percent titanium alloy gave the optimum overall performance. Its V_{50} limit velocity is 22 percent greater than the RHS of equal area density, and it has longer after-damage fatigue life. Increasing the volume fraction of aluminum is found to decrease the protection V_{50} limit and increase the after-damage fatigue life, and vice versa.

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INTRODUCTION

The purpose of this report is to suggest the way to attain exceptional ballistic penetration resistance and after-penetration fatigue-damage tolerance in metal/metal laminates. Although the optimum light-weight metallic laminate has not been perfected, the results of the exploratory tests of laminates reported here indicate the major factors of concern for optimizing performance.

Possible applications of the research are in

(a) light-weight armor for vehicles, vessels, and helicopters;

(b) structural components for helicopters and aircraft;

(c) crack arrester systems for aircraft and ships;

(d) concentrically laminated thick-wall pressure vessels.

This report is a sequel to one presented in the 1974 Army Science Conference,[1] in which the behavior and fatigue test results of steel laminates and aluminum laminates were presented. It was concluded then that damage tolerant metal laminates can be made by furnace brazing steel lamina or by explosive bonding Alclad 6061-T6 aluminum lamina. Also, fatigue crack retardation appeared to result from a "crack blunting" effect of plastic deformation at the interfaces, while fatigue crack arrest appeared to result from the crack turning into the direction of the interface and subsequent delamination.

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[1]Throop, J. F. and Miller, J. J., "Fatigue Behavior of Laminates," Proc. U.S. Army Science Conference, June 1974, Vol. III, pp. 229-243, AD785690.

That was followed by a paper published in 1978 on fracture resistant titanium/aluminum laminates[2] in which it was concluded that explosive bonding of alternate sheets of mill-annealed Ti-6AL-4V and Alclad 2024-T3 produces a laminate in which the fatigue crack rates, fracture toughness, and impact resistance are superior to those of the component alloys.

The present report attempts to indicate how such laminates may be developed with superior damage tolerance properties. It reports exploratory test results on the ballistic penetration resistance and after-penetration fatigue damage tolerance of three compositions of the titanium/aluminum laminates. Tests were made to compare their performance with that of rolled 6061-T6 aluminum alloy plate and that of rolled homogeneous steel (RHS) armor plate, using 0.30 caliber (44 grain) fragment simulator projectiles. The attributes of laminates which contribute to optimum performance are examined. An attempt was made to exploit as many attributes as possible in preparing the laminated materials for these tests.

BACKGROUND

Our early studies[1] were made with compact tension specimens, illustrated in Figure 1. We tested specimens of three configurations: (A) the crack arrest type in which a crack grown from a notch may be arrested by the interfaces between the composite layers, (B) the crack divider type, in which

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[1] Throop, J. F. and Miller, J. J., "Fatigue Behavior of Laminates," Proc. U.S. Army Science Conference, June 1974, Vol. III, pp. 229-243, AD785690.
[2] Throop, J. F. and Fujczak, R. R., "Fracture Resistant Titanium-Aluminum Laminate," Toughness and Fracture Behavior of Titanium, ASTM STP 651, American Society for Testing and Materials, 1978, pp. 246-266.

the crack growing from a notch is divided among the several layers, and (C) the coplanar type, in which the crack starting from a notch can be made to grow in the mid-thickness of a lamina for some distance before it veers into the bond layer and causes delamination of the bond.

The later work,[2] on the titanium/aluminum laminates, was done with bending specimens. Crack divider and crack arrest specimens were tested. In the crack arrest specimens the notch was made so that its tip was either in an aluminum layer or a titanium layer, and then grown through that layer by cyclic loading to determine if it would go through the next bond layer or be arrested at the interface and start cyclic delamination. After measuring the crack growth rate by loading with a cyclic bending moment, we stopped the cyclic loading and loaded with a monotonically increasing load to measure the specimen's fracture toughness. Similar small standard Charpy impact specimens were made and used to measure the impact energy absorption C_V in both orientations of the notch.

These prior test results showed that ducile interfaces tend to decrease fatigue crack propagation rates in both orientations, and greatly enhance impact resistance in the crack arrest orientation. For resistance to ballistic penetration the laminate must resist fracture in the crack arrest configuration due to impact of a projectile. For complete penetration of the projectile it is necessary for the projectile and the associated cracks to pass through the several layers and interfaces of the laminate. Energy

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[2]Throop, J. F. and Fujczak, R. R., "Fracture Resistant Titanium-Aluminum Laminate," Toughness and Fracture Behavior of Titanium, ASTM STP 651, American Society for Testing and Materials, 1978, pp. 246-266.

absorption by delamination and plastic deformation can be very effective in resisting penetration.

For subsequent fatigue service, however, the laminate must resist crack propagation in the crack divider orientation. The ballistically penetrated area may have so much damage that fatigue crack initiation is immediate and crack propagation life is very short. This is quite different from the usual fatigue crack propagation rate test in which a precracked specimen is cyclically loaded, or from a fracture toughness test in which a specimen is precracked and then monotonically loaded to failure. The ballistic penetration damage may be much more severe and the damaged area much more extensive than in the usual precracked specimen. It is appropriate then, to perform fatigue testing of specimens which have been subjected to actual ballistic damage.

FRACTURE THEORY

Our experiments have been guided by the Cook and Gordon 1964 adaptation[3] of the Griffith (1921) fracture theory showing what may happen as a crack approaches normal to the interface between two solid materials. They showed that in an all brittle system a fracture may develop perpendicular to the advancing crack and well ahead of it because the maximum tensile stress in the direction of the crack advance occurs ahead of the crack tip and may exceed the strength of the material there. This applies especially at a weak interface in the crack arrest configuration of a laminate, and results in delamination of the interface.

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[3]Cook, J. and Gordon, J. E., Proceedings Royal Society of London, Vol. 282A, 1964, pp. 508-520.

McCartney et al[4] showed that this accounts for the arrest of super-critical cracks at interfaces in impact of laminates and of sub-critical cracks in fatigue of laminates. They postulated that the phenomenon is governed by the interfacial fracture strength gradient and the plastic zone size at the tip of the advancing crack. Thus a crack may either go through an interface or be arrested by delamination of the interface, depending upon the gradient of strength at the interface and the radius of the crack tip plastic zone when the crack arrives at the interface.

Our work has led us to postulate that the criterion for crack arrest at an interface in a given metal/metal laminate may be expressed as a constant product of the interfacial strength gradient γ times the radius of the crack tip plastic zone, r_p. The gradient is predetermined by the strengths of the chosen metals and thickness of bond layer at the interface. The plastic zone radius varies with the change of stress and with the increase in crack depth and can be calculated in terms of the fracture mechanics stress intensity factor. If their product is too great, either because of too steep a strength gradient or too large a plastic zone, the crack cannot advance into the stronger metal and a fracture occurs in the weaker metal perpendicular to the advancing crack. Cyclic fatigue crack growth in the weaker metal along the interface then results in progressive delamination of the bond layer. In impact, the fracture of successive interfaces increases the energy absorption over that of the monolithic material.

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[4]McCartney, R. F., Richard, R. C., and Trozzo, P. S., "Fracture Behavior of Ultrahigh Strength Steel Laminar Composites," Trans. ASM, Vol. 60, 1967, pp. 384-389.

CRACK ARREST CRITERION

Postulating that the crack arrest criterion can be expressed as a constant product of γ times r_p gives

$$\gamma \, r_p = C \tag{1}$$

as the limiting condition for delamination.

One can approximate the measured interfacial strength gradient γ by

$$\gamma = \frac{S_1 - S_2}{0.25 \, t} \tag{2}$$

where S_1 is the ultimate tensile strength of the metal layer

S_2 is the ultimate tensile strength of the bond layer

t is the thickness of the bond layer

r_p is the crack tip plastic zone radius

C is a constant for a given composite

One can also approximate the crack tip plastic zone size for a static loading by the expression according to Irwin[5]

$$r_p^{s} = \frac{1}{2\pi} \frac{K^2}{S_y^{\,2}} \tag{3}$$

or for a cyclic loading by the expression according to Paris[6]

$$r_p^{c} = \frac{1}{8\pi} \frac{\Delta K^2}{S_y^{\,2}} \tag{4}$$

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[5]Irwin, G. R., "Fracture Mode Transition for a Crack Traversing a Plate," J. Basic Eng., Am. Soc. Mech. Eng., Series D, V. 82, No. 2, June 1960.
[6]Paris, P. C., "The Fracture Mechanics Approach to Fatigue," in Fatigue, An Interdisciplinary Approach, Burke, J. J., Reed, N. L., Weiss, V., Editors, Syracuse University Press (1964), pp. 107-132.

where S_y is the yield strength of material at the crack tip

$K = Y\sigma\sqrt{a}$, the stress intensity factor

ΔK is the cyclic range of stress intensity factor

Y is a term dependent upon the loading and geometry

a is the crack length

σ is the nominal stress

For a given combination of metal lamina, bond layer and bond thickness, the values of γ, S_y, and C are fixed and the likelihood of crack arrest by delamination depends upon the plastic zone radius at the crack tip. Thus

$$r_p = \frac{C}{\gamma} \tag{5}$$

indicates that a constant size plastic zone corresponds to the limiting condition for crack arrest by delamination.

Expressing this in terms of the fracture mechanics stress intensity factor, the condition for delamination becomes

$$K_{max} = \sqrt{2\pi}\, S_y \left(\frac{C}{\gamma}\right)^{1/2} \tag{6}$$

for crack arrest under static loading, and

$$\Delta K = \sqrt{8\pi}\, S_y \left(\frac{C}{\gamma}\right)^{1/2} \tag{7}$$

for crack arrest under cyclic loading. These indicate that the maximum stress intensity factor for delamination under cyclic loading is at least tw'ce that required for delamination under static loading, hence the tendency for delamination is greater under static loading. Since the crack tip plastic zone will be even larger under an impact loading the tendency for delamination

will be even greater under impact. Also, the delamination of successive bond layers under impact can absorb a large amount of energy in the deformation involved. These aspects of the hypothesis are in agreement with previously observed laminate behavior.

They also indicate that the criterion for crack arrest corresponds to a condition of constant K_{max} under static loading or of constant ΔK under cyclic loading. This has suggested an experiment for testing the validity of the hypothesis.

Experimental confirmation of the postulated crack arrest criterion has been demonstrated in a load shedding fatigue experiment in which it was possible to make a fatigue crack go through an interface by staying below the limiting value of ΔK, or make it be arrested by bond layer delamination by exceeding the limiting value of ΔK.

From Equation (7) and the stress intensity K-calibration for a given specimen type one can solve for the load to keep ΔK constant and corresponding to the criterion for crack arrest by delamination. For the compact tension specimen[7]

$$\Delta K = \frac{\Delta P}{BW^{1/2}} f(a/W) \tag{8}$$

From this and Equation (7) one gets

$$\Delta P = \frac{1}{f(a/W)} [\sqrt{8\pi}\ BW^{1/2}\ S_y \left(\frac{C}{\gamma}\right)^{1/2} \tag{9}$$

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[7]ASTM Specification E-399-78, 1978 Annual Book of ASTM Standards, Part 10, Am. Soc. Test & Matls., Philadelphia, PA, pp. 512-533.

Similar expressions can be written for 3-point bending specimens[7] and for pure bending specimens.[8] Since the terms within the brackets are all constants, Equation (9) indicates that in order to maintain a constant value of ΔK the cyclic load must be reduced as the inverse of $f(a/W)$. When the cyclic load is kept less than ΔP from Equation (9) the fatigue crack will grow through the interface and into the next metal layer. Reducing the load before reaching each successive bond layer permits the fatigue crack to grow through several layers. If, however, the load is not reduced below the limiting value the crack will be arrested and cyclic delamination will occur at the next interface it arrives at. To apply these expressions to any given laminate composition one must evaluate S_y, γ, and C experimentally for that laminate.

Figure 2 is an illustration of this load-shedding experiment. This is a plot of data from specimen A3A, a laminated beam of 6061-T6 explosively bonded with 0.012 inch thick 7072 aluminum alloy Alclad bond layers. It was fatigue cycled in pure bending under the prescribed load shedding procedure so that the load ΔP was kept less than the crack arrest limit as the crack approached each successive bond layer. The open circles represent the fatigue crack going through the interface at the load and crack depth plotted. Solid circles for other specimens represent the delamination and arrest of the crack at an interface corresponding to the plotted load and crack depth.

One can see that in specimen A3A the load shedding kept the stress intensity factor range ΔK less than the value of 12 $\text{Ksi}\sqrt{\text{in}}$ and the crack

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[7]ASTM Specification E-399-78, 1978 Annual Book of ASTM Standards, Part 10, Am. Soc. Test & Matls., Philadelphia, PA, pp. 512-533.

[8]Tada, H., Paris, P., and Irwin, G., "The Stress Analysis of Cracks Handbook," Del Research Corporation, Hellertown, PA, 1973, p. 214.

proceeded through five successive bond layers before delamination occurred at the sixth. In the other specimens crack arrest and delamination occurred at interfaces at similar loads and crack depths because the loads were not reduced below the limiting value. This experiment has been performed successfully in several other metal lamina and bond layer combinations.

CRACK RETARDATION

Even when the crack grows through the bond layer its growth is retarded, as shown in Figure 3. The curve labelled A shows fatigue crack growth in a crack arrester specimen of the Ti/AL laminate. The curve labelled B shows the fatigue crack growth on a crack divider specimen of the same laminate under the same loading conditions. As the crack approaches the bond layer in the crack arrester specimen (A) it slows down in the 2024 aluminum layer and takes a large number of cycles to traverse the soft Alclad bond layer. When it grows into the next Ti-6AL-4V layer it acquires approximately the same crack rate as that in the crack divider specimen, but as it approaches the next bond layer it again slows down. This repetitive retardation of crack growth at each interface has the cumulative effect of greatly lengthening the fatigue crack propagation life in comparison to monolithic specimens of the same materials or to crack divider specimens of the same laminate. We have previously shown that the crack rates of the Ti/AL laminates in both crack divider configuration and crack arrest configuration are less than those of the component material.[2] Thus, even in the crack divider configuration the

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[2]Throop, J. F. and Fujczak, R. R., "Fracture Resistant Titanium-Aluminum Laminate," Toughness and Fracture Behavior of Titanium, ASTM STP 651, American Society for Testing and Materials, 1978, pp. 246-266.

bond layers have some effect on the fatigue crack rate. This may be attributed to energy absorption and crack blunting in the soft bond layers, and to a tendency for plane stress behavior in the individual lamina.

BALLISTIC DAMAGE SPECIMENS

In the present study small plate specimens were prepared as shown in Figure 4, and tested first for their ballistic penetration resistance. Then loading holes were drilled and a saw cut was made into the ballistically damaged area and the specimens were tested as compact tension specimens for their after-damage fatigue life.

In Figure 4 the edge view labelled (A) shows the arrangement with 30 percent volume fraction of aluminum, the view labelled (B) shows the arrangement with 60 percent volume fraction and view labelled (C) shows the arrangement with 90 percent volume fraction. The shaded layers represent the titanium layers. The layer and laminate thicknesses are given in Table I. Similar specimens were made of 6061-T6 plate and RHS armor plate, also listed in Table I.

MATERIALS

The laminates for these specimens were composed of mill-annealed Ti-6Al-4V sheets and Alclad 2024-T3 aluminum alloy sheets, clad on both sides. In the finished laminates the thickness of the cladding was approximately 0.002 inch. In each composite the titanium sheets were interior layers and the exterior layers were Alclad aluminum alloy sheets.

TABLE I. DESCRIPTION OF MATERIALS AS PREPARED FOR TEST

	Aluminum		Titanium		Laminate		
Material Designation	No. of Layers (#)	Thick-ness (inch)	No. of Layers (#)	Thick-ness (inch)	Thick-ness (inch)	AL Vol. Fract. (%)	Areal Density (lb./sq. ft.)
Ti/AL-AA	3	0.031	2	0.120	0.333	28%	6.38
Ti/AL-AB	3	0.080	2	0.080	0.400	60%	6.71
Ti/AL-AC	2	0.190	1	0.045	0.425	89%	6.13
6061-T6 AL	1	-	0	-	0.381	100%	5.28
RHS Armor	0	-	0	-	0.150	0%	6.12

These consisted of a five-layer laminate (AA) with three thin aluminum layers and two thick titanium layers, having approximately 30 percent volume fraction of aluminum; a five-layer laminate (AB) with three aluminum layers and two titanium layers all of equal thickness, having 60 percent volume fraction of aluminum; also a three layer laminate (AC) with two thick layers of aluminum and one thin layer of titanium, having approximately 90 percent volume fraction of aluminum. They were laminated by explosive bonding in the Fabrication and Quality Assurance Section of the Battelle Columbus Laboratories.[9] They were compared with plates of 6061-T6 aluminum alloy and rolled homogeneous steel armor RHS. The five materials tested are listed with their layer dimensions in Table I.

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[9]Pattee, H. E., "Explosive Welding of Laminated Plates," Final Report to Watervliet Arsenal From the Fabrication and Quality Assurance Section of Battelle Columbus Laboratories, Columbus, OH, August 1979.

The 3/8 inch thick plate of 6061-T6 aluminum alloy and the 0.150 inch thick plate of homogeneous rolled steel armor (RHS) were supplied by the Fort Dix Test Facility of ARRADCOM, where the ballistic penetration testing was performed.[10]

An attempt was made to have the laminated materials about 3/8 inch thick to compare with the 6061-T6 aluminum plate, and to approximate as nearly as possible the areal density of 6.12 pounds per square foot of the RHS plate, so as to facilitate the comparison of ballistic penetration and fatigue performance. In the final analysis the ballistic penetration velocities of the laminates and the aluminum were compared with published[10,11] values for RHS having the same areal density as that of each of these materials.

BALLISTIC PROTECTION VELOCITY

The ballistic penetration tests were made by supporting the plate specimen against a steel plate with a two inch diameter hole in it at the point where the bore-sited projectile was aimed. Fragment similator projectiles of 0.30 caliber (44 grain) were fired at various velocities to obtain the ballistic protection velocity limit V_{50} at which 50 percent of the projectiles would just penetrate through the specimen. The resulting values of V_{50} for the materials tested are compared with V_{50} values for RHS of the same areal density in Table II.

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[10]Webster, E. A., Private Communication and letter from James A. Donahue, Director, ARRADCOM, Test Site, Fort Dix, NJ, February and March 1980.
[11]AMMRC, "Ballistic Technology of Lightweight Armor," TR79-10, U.S. Army Materials and Mechanics Research Center, 1979 (U), Figure 410.

TABLE II. COMPARISON OF BALLISTIC PROTECTION VELOCITIES

Material Tested	Thickness (inch)	Areal Density lb/sq. ft.	Test V_{50} ft/sec	RHS, V_{50} ft/sec	Ratio: $\frac{\text{Test}}{\text{RHS}}$
6061-T6	0.381	5.28	1660	2041	0.81
RHS	0.150	6.12	2170	2267	0.96
Ti/AL-AC 90% AL	0.425	6.13	2400	2270	1.06
Ti/AL-AA 30% AL	0.333	6.38	2850	2338	1.22
Ti/AL-AB 60% AL	0.400	6.71	2950	2427	1.22

AREAL DENSITY

Figure 5 shows a plot of the volume fraction F_a of aluminum of the laminates versus the areal density a in pounds per square foot. The line shows the variation of F_a versus d for 3/8 inch laminate. The symbols on the graph show the volume fraction versus density of the laminates tested and their thickness, as well as that of the 6061 plate. The right side of Figure 5 shows the V_{50} of the laminates and the 6061-T6 plotted as a function of their areal density. The equation of the curve shown indicates that the V_{50} increases as the square of the areal density. The values of V_{50} of the three laminates exceed that of the RHS which had the areal density of 6.12 pounds per square foot, while that of 2024-T4 is slightly less and that of 6061-T6 is considerably less. These results will be compared with RHS on the basis of equal areal densities in a later section. The curve on Figure 5 indicates

that the ballistic protection velocity V_{50} decreases in relation to the square power of the volume fraction of aluminum in the laminate. The interpretation is that the more titanium there is in the laminate the greater the V_{50} protection limit will be.

FATIGUE LIVES

The number of fatigue cycles endured to failure for each of the ballistically damaged materials is listed in Table III. In all three laminates, and the 6061-T6 as well, the lives of the drilled-hole specimens are much longer than those of the ballistically damaged specimens. It may be assumed that the ballistic damage practically eliminates the fatigue crack initiation cycles that are included in the lives for the drilled-hole specimens, and also that the damage extends to a larger radius from the center of the damage site.

TABLE III. AFTER-DAMAGE FATIGUE TEST RESULTS

Material Tested	Aluminum Vol. %	$\left(\frac{V_{50}}{V_{RHS}}\right)^*$	N_f (Cycles)	$\left(\frac{N_f}{N_{RHS}}\right)$
6061-T6	100%	0.81	61,000	1.7
Ti/AL-AC	90%	1.06	128,000	3.6
Ti/AL-AB	60%	1.22	58,000	1.6
Ti/AL-AA	30%	1.22	27,000	0.7
RHS	0%	0.96	36,000	1.0

Only the fatigue lives of those specimens which were impacted at the V_{50} velocity of the particular laminate or near it are amenable to consistent analysis. The ones that were only partially penetrated would have endured longer lives than measured if we had not made our saw cut to the middle of the damaged zone, because the fatigue cracks would have had to grow in the crack arrest orientation until they became through-cracks before growing in the crack divider orientation. The lives of the specimens which were penetrated at greater than the V_{50} velocity are quite variable because of the greater extent of damage from the higher velocity. Their lives are much shorter in general than those which were impacted at the V_{50}.

Focusing our attention on those which were impacted at velocities close to the V_{50} for each material, one may see in Figure 6 that the greater V_{50} velocity of the material the longer the fatigue life of the specimen at the given cycle load. These were all cycled at the same load, specifically from 175 lb. to 1,750 lb. and at 30 hertz. The triangle symbols represent ballistically damaged specimens, and the circles represent drilled-hole specimens of the laminates and the 6061-T6 plate.

Figure 6 also indicates that the greater the volume fraction of aluminum in the laminate the longer the fatigue life will be. Both AB and AC, as well as the 6061 aluminum plate have lives greater than the RHS specimens. The equation on Figure 6 indicates that the fatigue life of the 90 to 100 percent volume fraction specimens increases with the square root of V_{50}. The V_{50} was shown earlier to increase as the square of the areal density. Hence the fatigue life for 90 to 100 percent AL is seen to increase approximately as the areal density. However, the three curves representing 30 percent,

60 percent, and 90 percent volume fraction of aluminum indicate that the larger the aluminum content the longer is the after-damage fatigue life of the laminate.

It becomes apparent then that to optimize the laminate's performance in both ballistic penetration protection and after-damage fatigue tolerance, one must make a compromise in regard to the aluminum volume fraction, since decreasing F_a increases V_{50} but decreases N_f. On Figure 7 is plotted V_{50} for each material divided by the V_{50} of equal areal density RHS. Also plotted is N_f divided by the N_f of the 0.150 inch thick RHS tested. This shows that the best after-damage fatigue life is given by the 90 percent aluminum laminate. However, the best combination of ballistic protection velocity with fatigue life is given by the 60 percent aluminum laminate, with a V_{50} which is 22 percent greater than the RHS, and a fatigue life which is over 50 percent longer than the RHS.

LAMINATE ATTRIBUTES

From the results reported earlier[1,2] and those reported here it is evident that there are several aspects of metal/metal laminates which can be exploited to develop maximum damage tolerance. Each of the following attributes of laminate construction can be enhanced toward optimizing the laminate performance for a given application. In the titanium/aluminum laminates they are:

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[1]Throop, J. F. and Miller, J. J., "Fatigue Behavior of Laminates," Proc. U.S. Army Science Conference, June 1974, Vol. III, pp. 229-243, AD785690.
[2]Throop, J. F. and Fujczak, R. R., "Fracture Resistant Titanium-Aluminum Laminate," Toughness and Fracture Behavior of Titanium, ASTM STP 651, American Society for Testing and Materials, 1978, pp. 246-266.

1. Alternate soft and hard layers: Soft layers absorb energy and resist spalling of the hard layers, while the hard layers provide high strength. Soft Alclad layers on the exterior surfaces also resist corrosion from the surrounding environment.

2. Thin-sheet metal properties can be retained in thick sections: Superior mechanical properties are attainable in rolled sheet as compared to thick forged sections; heat treatment is more effective and plane stress K_c fracture toughness, rather than plane strain K_{Ic}, may be sustained.

3. Ductile bond layers resist fatigue and fracture: The Alclad surfaces on the aluminum sheets became the ductile bond layers and gave the effect of "crack blunting" at the interfaces. In steel laminates a ductile CuNi interleaf gave the same effect.

4. Laminate interfaces may be tailored to the application: The strength and thickness of the bond layer can be selected in relation to those of the metal layers so as to absorb energy, retard crack propagation and arrest cracks by delamination.

5. Favorable residual stresses can be developed by explosive bonding: Compressive residual stress in the aluminum layers retards initiation and propagation of fatigue cracks and increases the critical crack depth. The corresponding tensile residual stress in the alternate layers of higher-strength titanium tends to accelerate initiation and decrease the critical crack depth, but has little effect on the crack propagation rate and small effect on the after-penetration life.

6. <u>Areal density of the composite can be adjusted</u> from that of aluminum plate to that of titanium plate: The lighter weight permits thicker sections than steel of the same areal density, hence panels may be stiffer.

7. <u>Volume fractions may be optimized</u> by adjusting the number and thicknesses of layers: Increasing the volume fraction of aluminum in the Ti/AL laminate increases the after-penetration fatigue life but decreases the ballistic penetration protection velocity.

Since most of these attributes are interdependent it is important to seek the optimum combination of all of them if maximum performance is to be attained. However, as long as alternate soft and hard layers of thin sheet metal are bonded with suitable ductile bond layers it is possible to adjust the thicknesses, strengths, and numbers of interfaces and lamina to give a range of areal density and volume fraction as desired. Explosive bonding, in addition, permits lamination of dissimilar metals without brittle interfaces.

CONCLUSIONS

1. Delamination at ductile interfaces in metal/metal laminates can absorb much energy in impact and ballistic penetration, and can retard or arrest fatigue cracks in cyclic loading.

2. The results of exploratory tests show that a compromise between the ballistic penetration protection velocity limit and after-damage fatigue life may be necessary to achieve the optimum combination of these two qualities in a laminate.

3. The several attributes of metal/metal laminates which contribute to the above qualities are interdependent, therefore it is necessary to seek

the optimum combination of these attributes to attain maximum performance of any given laminate composition.

4. An empirical criterion for crack arrest by delamination of laminate interfaces can be expressed in terms of the strengths and dimensions of the composite layers and as a function of a limiting value of the crack tip stress intensity factor.

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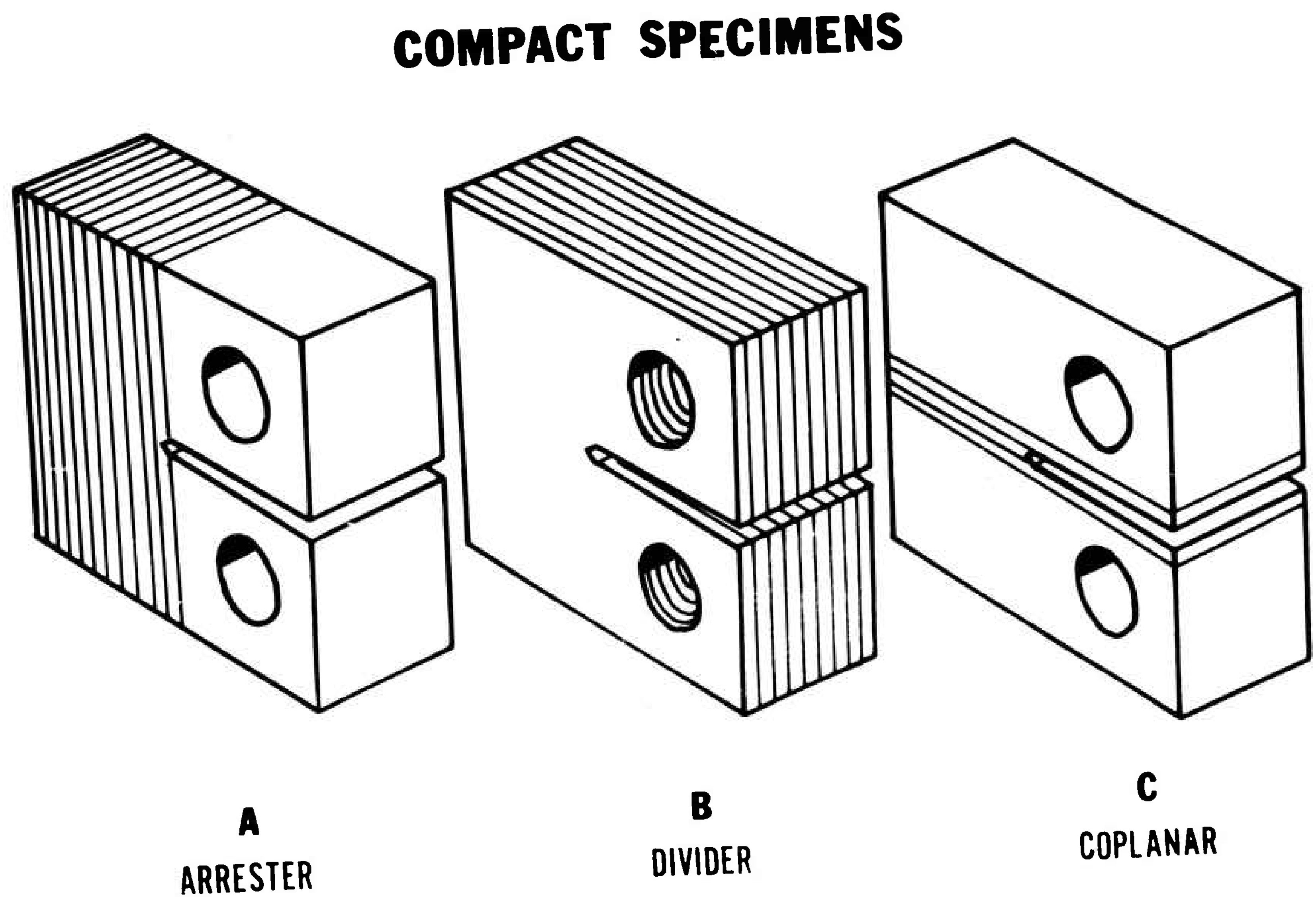

Figure 1. Compact Tension Specimens Showing Orientation of Laminations.

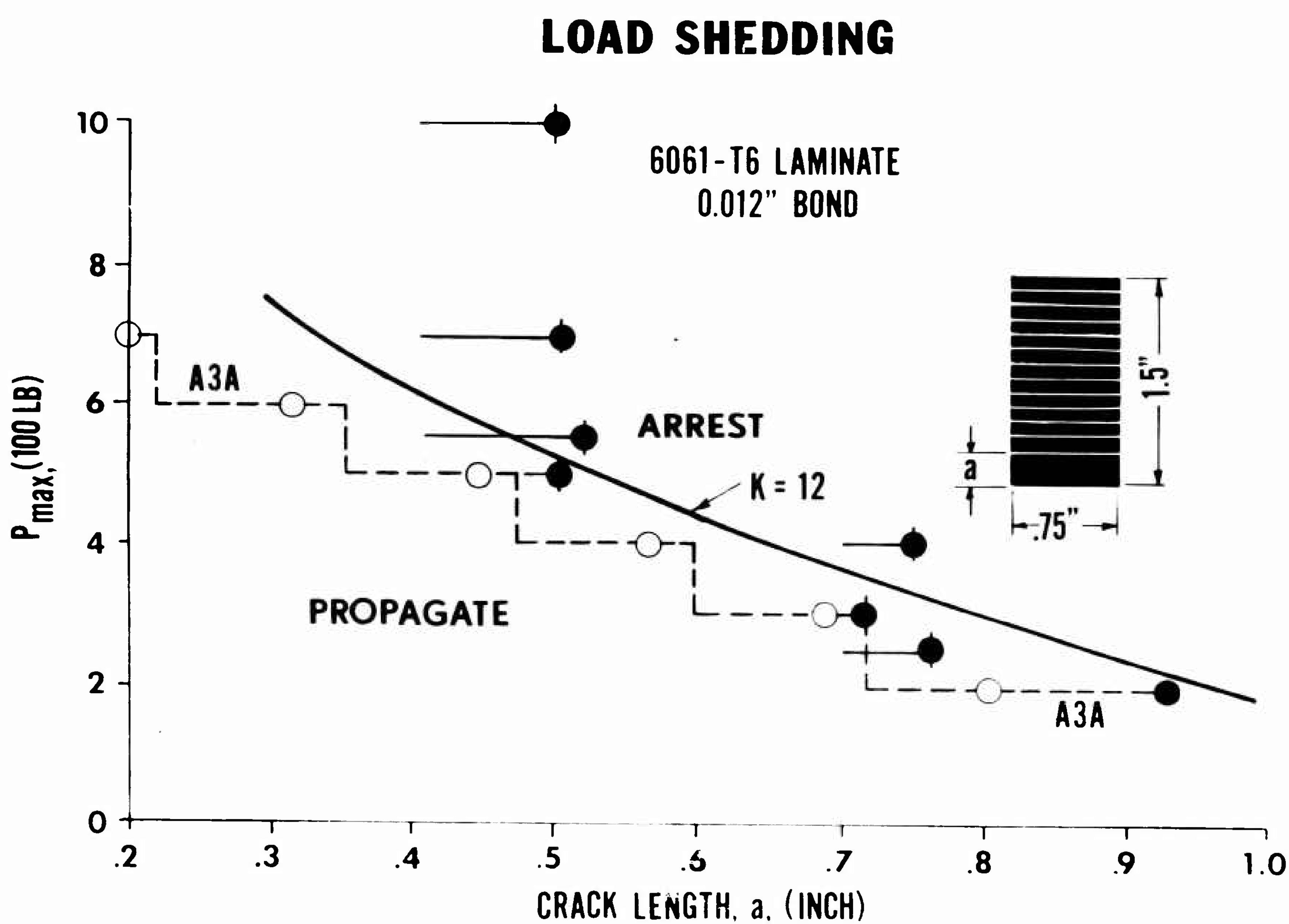

Figure 2. Load Shedding Experiment. The Dark Circles Represent Arrested Cracks.

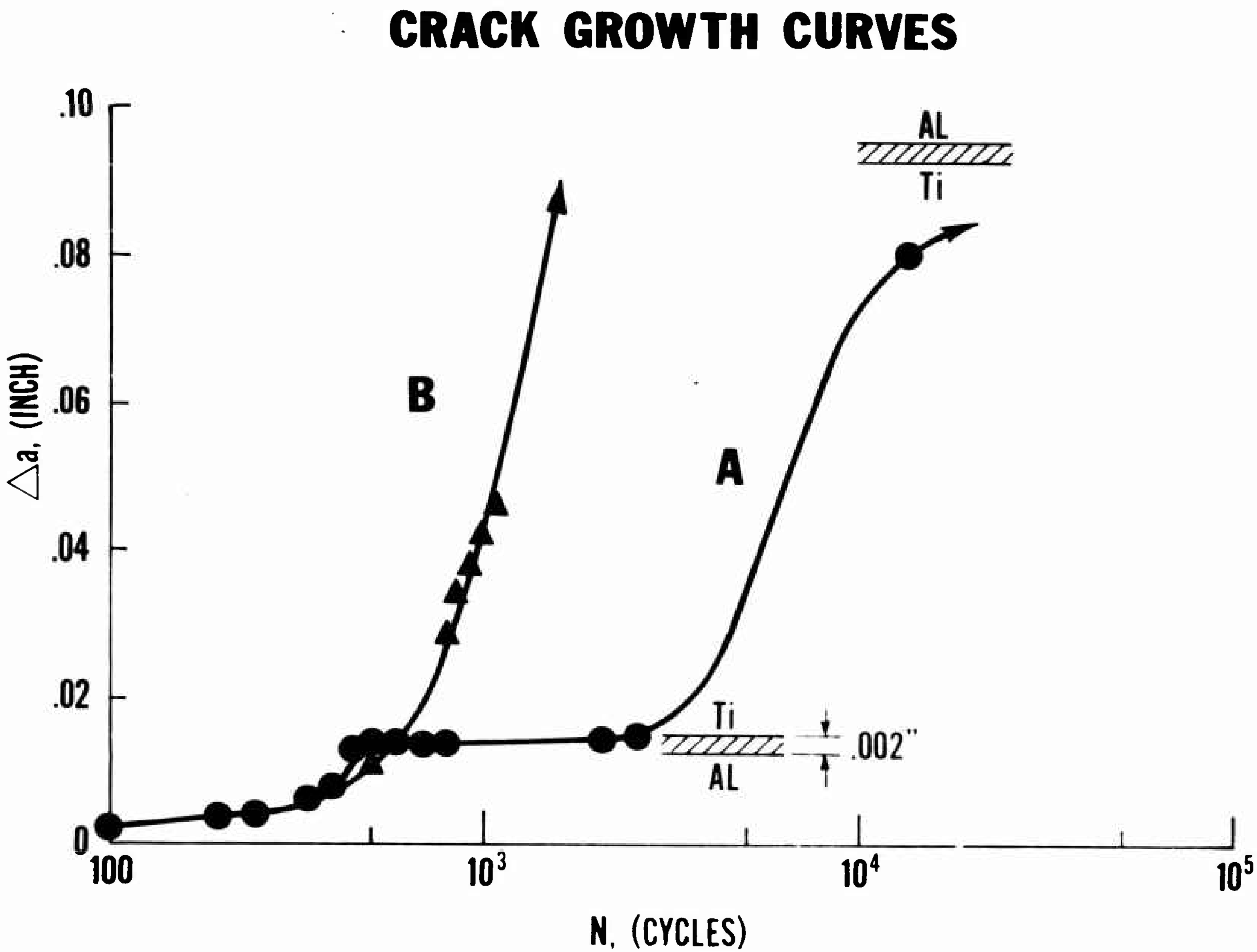

Figure 3. Fatigue Crack Growth in (A) Crack Arrester Specimen and (B) Crack Divider Specimen of Ti/AL Laminate.

BALLISTIC SPECIMENS

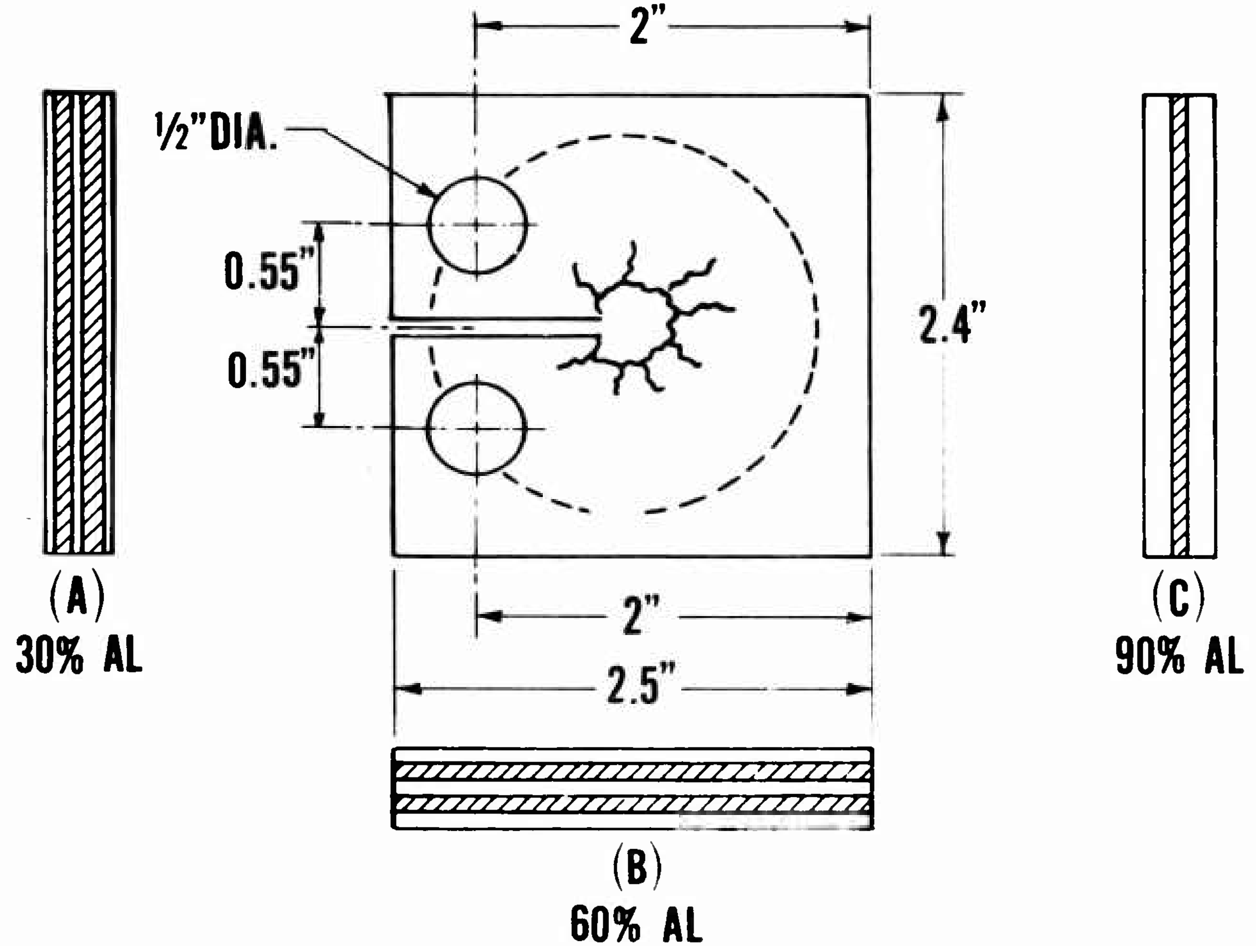

Figure 4. Plate Specimen Tested for Ballistic Penetration and After-Damage Fatigue Life.

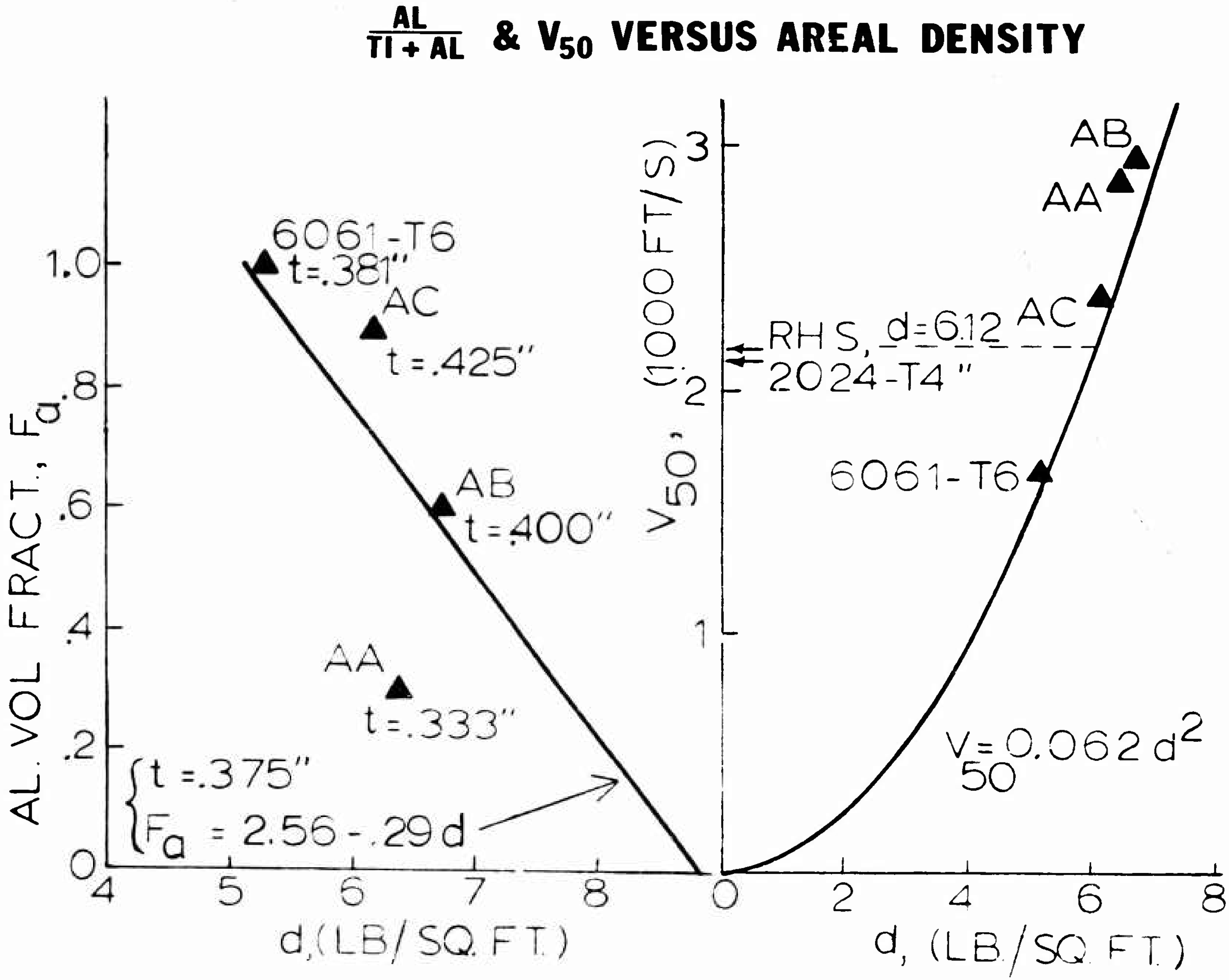

Figure 5. Volume Fraction of Aluminum, Fa, and Ballistic Penetration Velocity, V_{50}, Versus Areal Density

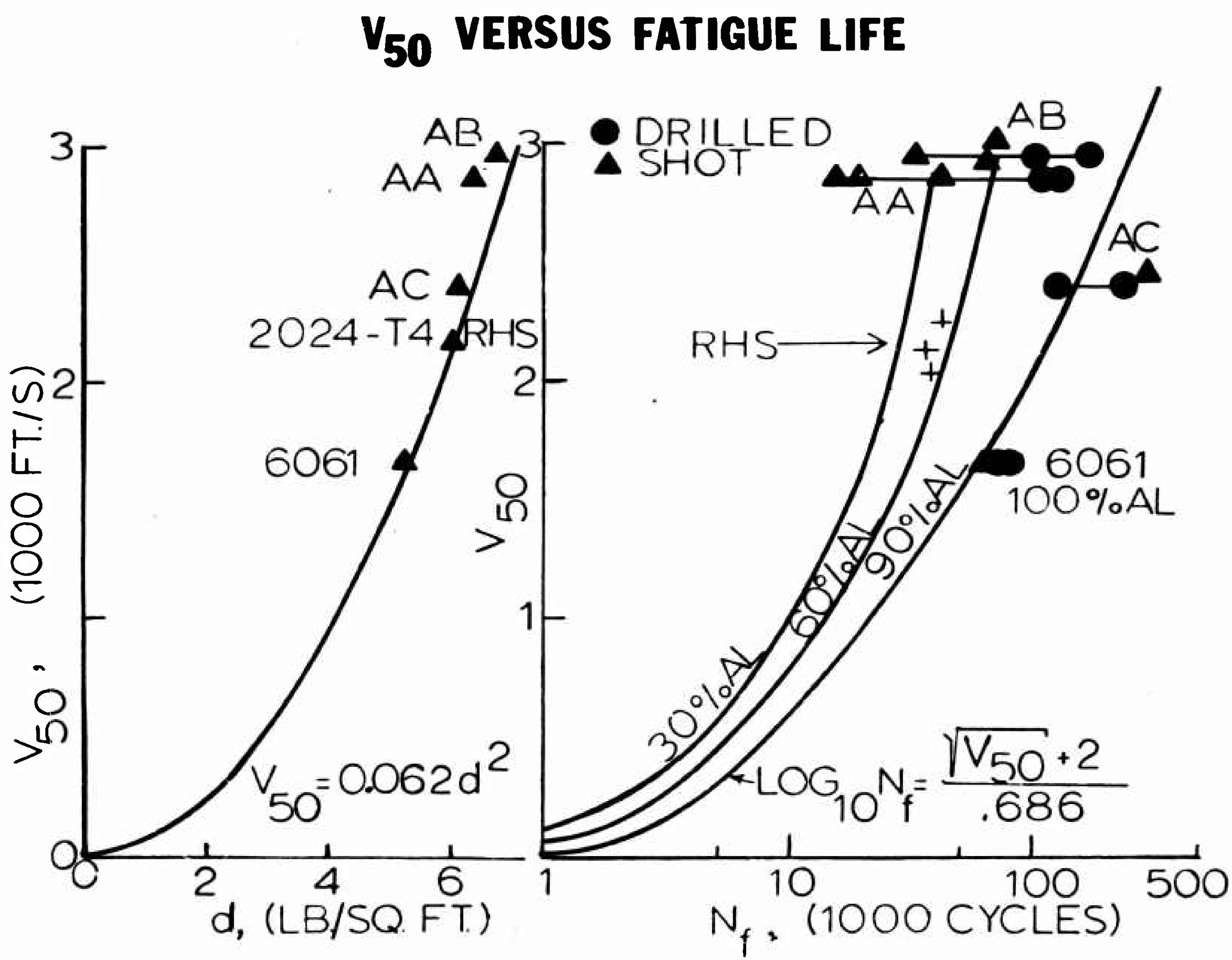

Figure 6. Relation Between Areal Density, Ballistic Penetration Velocity, V_{50}, and Fatigue Life.

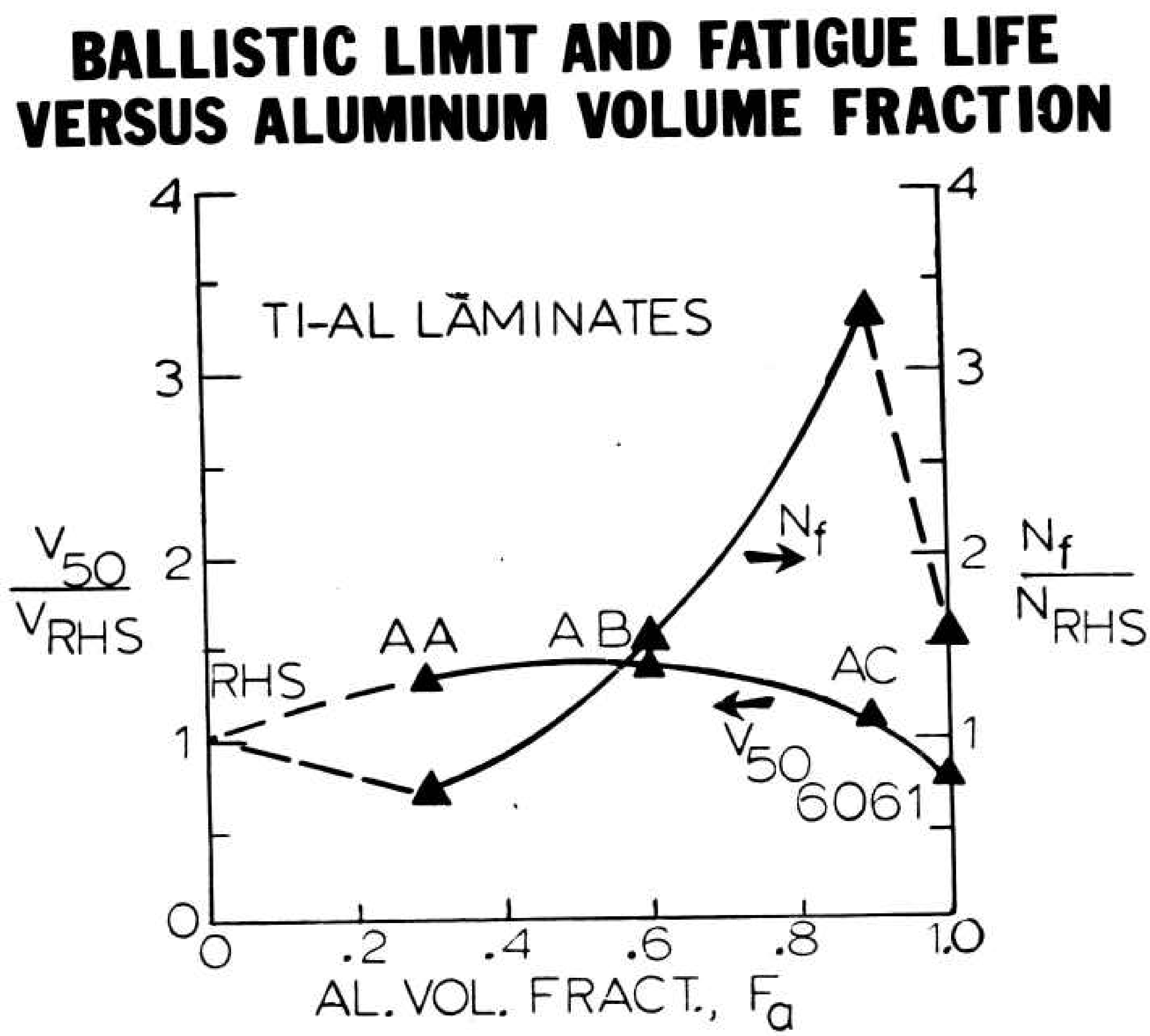

Figure 7. Ballistic Penetration Velocity Relative to that of Steel and Fatigue Life Relative to that of Steel Versus Aluminum Volume Fraction.

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